A First Look at NuMI Intensity Measuring Device Calibration

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Intensity Measuring Devices

Three sensors are used to measure the NuMI proton intensity. The first device is a DC current transformer (DCCT), which measures the intensity in the Main Injector. The other two are toroids (Pearson Current Transformers Model 3100) and measure the intensity at the beginning (Tor101) and, just before the target (Tortgt), of the NuMI beam line. Toroids are essentially transformers; the beam acting as the primary winding, induces a flux in the core, which in turn, creates a current in the secondary windings. The current is integrated over the pulse and used to determine the intensity. The beam loss along the line is usually less than 10e-4 and the toroids should essentially output the same result. Both toroids have two outputs with different resolutions. The results of the two outputs were compared and deemed equivalent. However, the 16 bit output was used in this study because it has higher resolution. The toroid names are annotated with a ‘d’ at the end to distinguish the higher resolution data.

The DCCT is a much more complicated device. In principle it feeds a modulated current through two oppositely wound toroids. Due to the non-linearity of the core-material’s hysteresis behavior, the toroid outputs are shifted in phase. When the offset reaches a maximum the DC current can be related to the second harmonic of the frequency of the modulated current. The AC component is detected and the two signals are sent through a feedback loop to cancel the primary current flux, eliminating AC contamination. The output current is determined by a voltage reading across a burden resistor.

Detector Calibration

The calibration process for the toroids consists of sending a known pulse through the sensor and measuring the response. This is repeated over a range of intensities, and results are used to calculate any offsets, which are then corrected for. The calibration can also depend on the properties of the gate. The gate refers to the period of time over which the current through a toroid is integrated. The gate is opened in reference to the timing of the NuMI kicker, and remains open for 100 usec. A bunch of up to six, 1.6 usec, batches (spaced by 94 nsec) can be sent through during this period, for a total time of up to 10 usec. (The relatively large gate size is an initial setting ensuring that the entire pulse is captured.) For calibration purposes a single 1.6 usec pulse is sent through 2.6 usec after the gate is opened. However, it has been determined, by stepping the pulse through the gate, that the position of the pulse relative to the leading edge of the gate can greatly affect the output (See Figure 1). There is a 0.15% change per usec leading to a 15% error across the gate. This implies that not only will the measured intensity value be affected by its gate position, but there will also be some variation across the batches. Correctly determining the batch position in reference to the calibration pulse position in the gate is imperative to correct calibration.

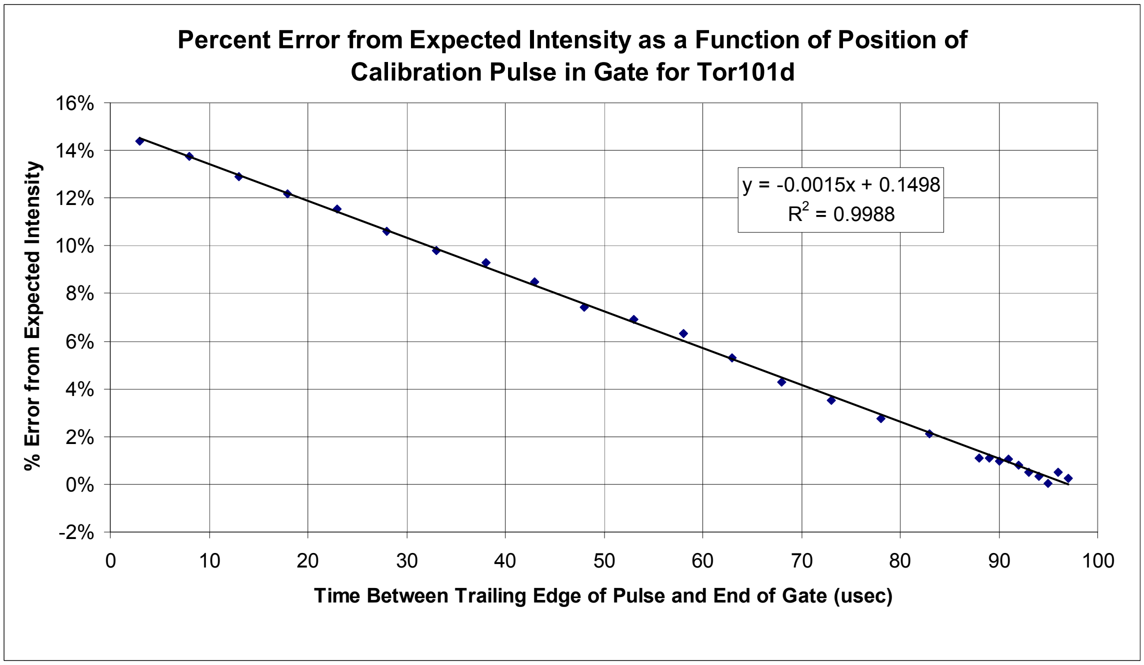

Figure 1: The input current and therefore the expected intensity do not change as the pulse steps through the gate. However, the output from the integrator increases 0.15% per usec.

Although the DCCT is relatively complex and, harder to diagnose, in comparison to the toroids, it is much less difficult to calibrate. For the most part DCCT's, unlike toroids, are not sensitive to the shape, or position of the bunch. (Response to the peak current at high RF frequencies can cause oscillations in the feedback loop resulting in nonsensical output.) Therefore, a simple DC current of less than 600 mA is necessary, as opposed to the full scale (100 V) pulsed signal, ideal for toroid calibration. Additionally, the DCCT has been used by other experiments which utilize the Main Injector, and there has not been a similar discrepancy reported. This suggests that the DCCT functions, and is calibrated correctly.

NuMI Activity

Data for this investigation was collected from the ACNET data logger over the period of February 18th, until March 23rd. The beam was activated on the 18th, and was run at various intensities, and spill rates through the 23rd, with the intensity and rate generally increasing as time passed. At times the Main Injector was run in mixed mode (one batch, with slipstacking, goes to antiproton source while the other five batches go to NuMI). During these periods not all of the Main Injector beam goes to NuMI, and the DCCT data can not be compared to that of the toroids. Therefore, NuMI only runs were selected from the data, and used for comparing the DCCT with the two toroids. On the 23rd the beam was turned off due to problems with the target. The three sensors were calibrated prior to the February 18th start date, and were not recalibrated until after the 23rd of March.

Analysis

Toroid and DCCT readings were taken from the ACNET data logger. If all three sensors did not produce a reading for a certain pulse the data for that pulse was discarded. The data was then separated into two sets; just the Tor101d and Tortgtd data for all runs, and data from all three sensors for NuMI only runs. These two data sets were then binned by intensity in bins every 1e12 protons. The ratios of the intensities were calculated, and the average intensities and the average ratios were found in each bin for the three sensors. The standard deviation of the averages was also calculated. There were periods of time when the sensors were taking data but no beam was being sent. Data from these periods were also compiled and binned every six hours. The results indicate the pedestal offsets for the three sensors.

The average intensities were plotted against each other, and linear regression analysis was preformed. The equations for the linear fits gives a measure of the combined pedestal offsets (y-intercept), and the percent difference between the two measurements (slope minus one). The two toroids are off by a factor of about 1%, while Tor101, and Tortgt differ from the DCCT by around 5%, and 4%, respectively. The three results are self consistent. The error bars indicate the standard deviation of the mean that is each data point. The small standard deviations, along with the value of unity for the square of the correlation coefficient, suggest that statistical errors are small and the effects seen are due to systematic errors.

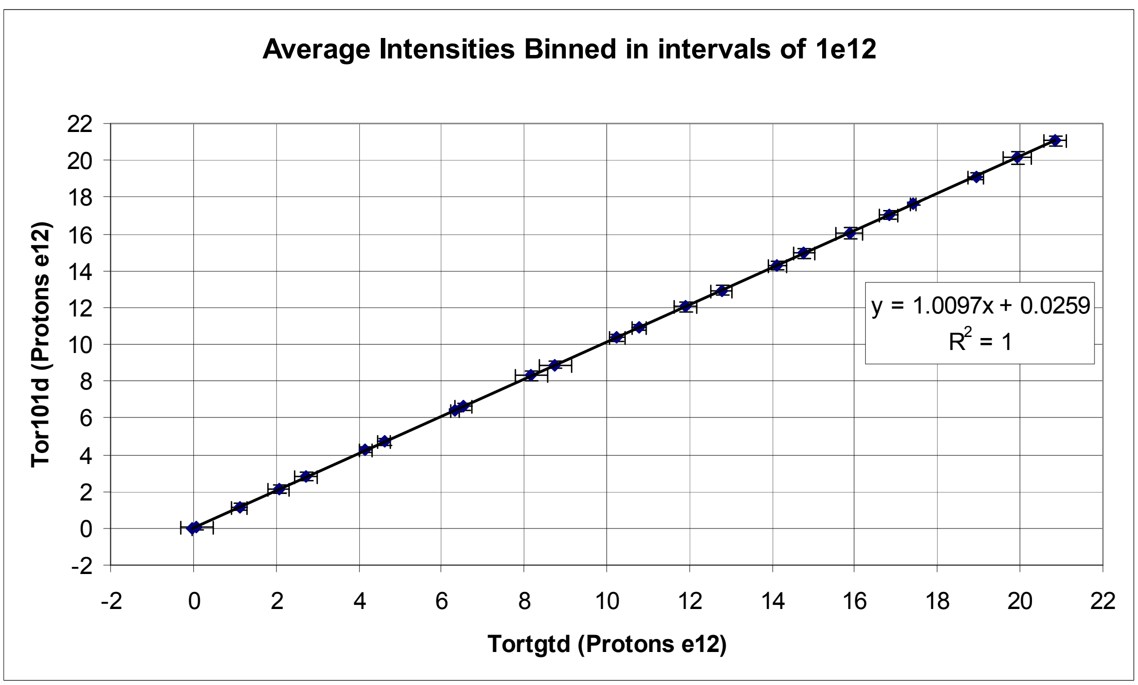

Figure 2: Mean Tor101d intensity plotted against mean Tortgtd intensity with linear fit

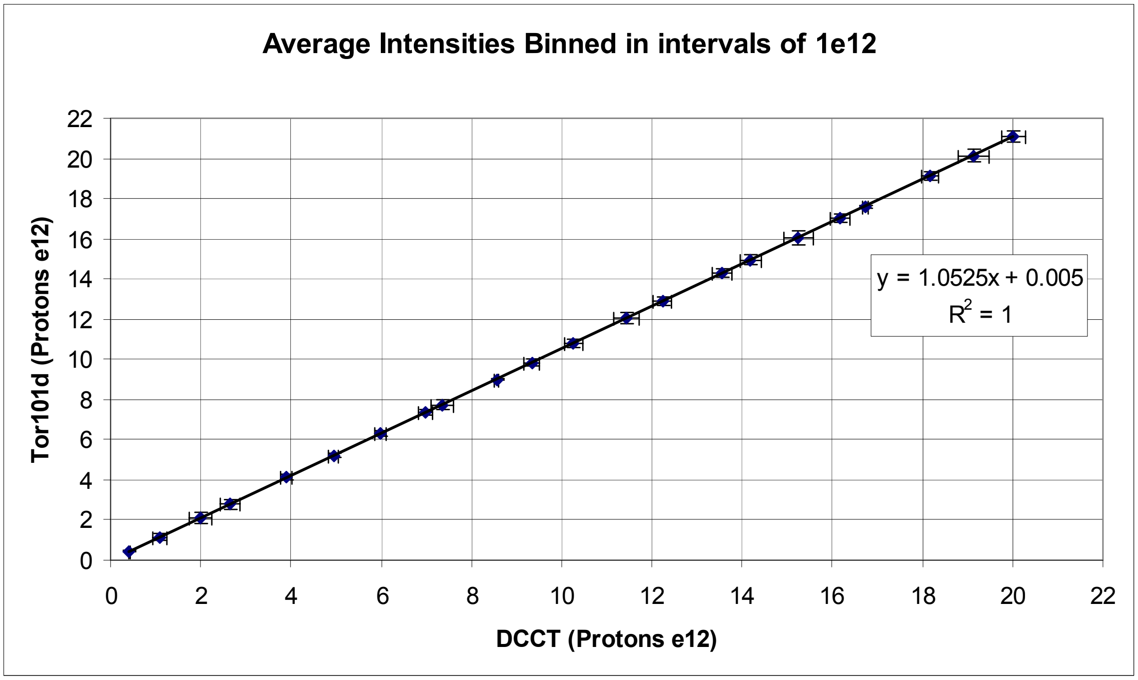

Figure 3: Mean Tor101d intensity plotted against mean DCCT intensity with linear fit

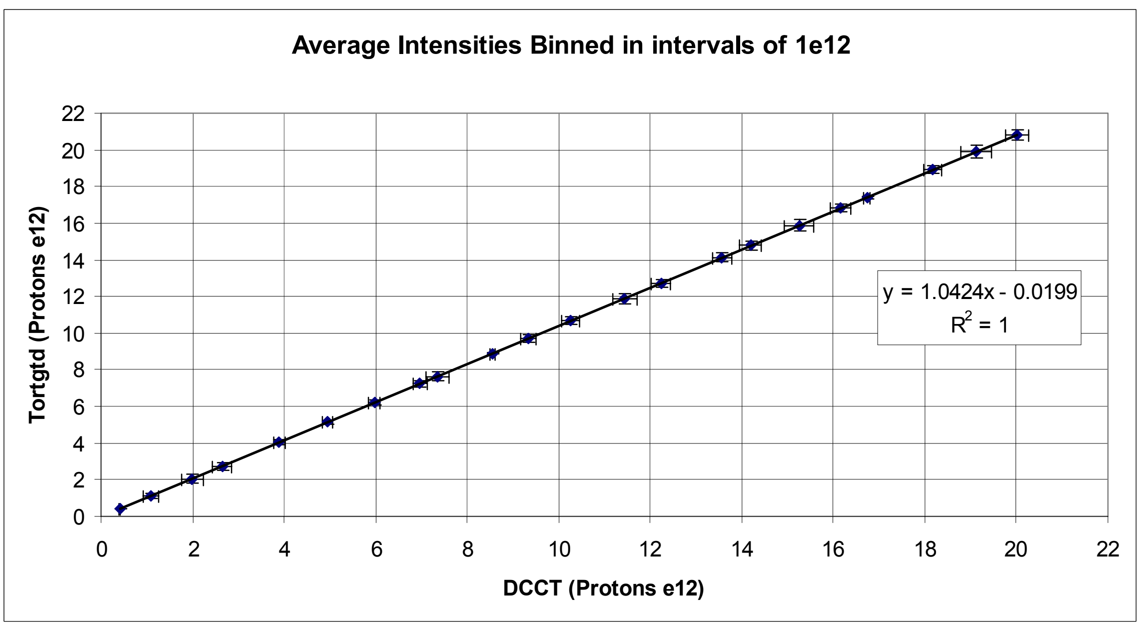

Figure 4: Mean Tortgtd intensity plotted against mean DCCT intensity with linear fit

The ratios of Tor101 to Tortgt and Tor101 to the DCCT were plotted against Tor101 intensities, and the ratio of Tortgt to the DCCT was plotted against Tortgt intensities. Furthermore, one can assume that each sensor measures the actual intensity times a linear coefficient plus an offset. (I.e. y = mx + b, where y is the measurement, x is the actual intensity, m is the linear coefficient, and b is the offset.) For simplicity assign a, c, and e to the linear coefficients for Tor101, Tortgt, and the DCCT, respectively, and similarly assign b, d, and f, to their respective offsets. One can now see that the slope of the intensity versus intensity plots is characterized by the appropriate ratios of the linear coefficients, while the intercepts of these plots can be found as a combination of offsets and ratio the linear coefficients

$$Tor101 = ax + b$$
$$Tortgt = cx + d$$
$$DCCT = ex + f$$

Solving for each for x and setting equal yields:

$$\frac{Tor101 - b}{a} = \frac{Tortgt - d}{c} = \frac{DCCT - f}{e}$$

Solving, now, for Tor101 gives:

$$Tor101 = \frac{a}{c}Tortgt - \frac{a}{c}d + b = \frac{a}{e}DCCT - \frac{a}{e}f + b$$

One can easily solve for Tortgt or the DCCT in a similar manner. For the Tor101 versus Tortgt plot, a/c is the slope, while b – (a/c)d is the y-intercept. One can also use this formulation to investigate the ratios of the intensities. For example:

$$\frac{Tor101}{Tortgt} = \frac{ax + b}{cx + d}$$

Therefore, as x, the actual intensity, tends toward infinity the ratio should tend towards a/c. In these plots, as the measured intensity (x-axis) becomes large the ratio (y-axis) should also tend towards the ratio of the slopes of the relevant linear fits from the previous set of plots. This relationship was found to be true for all three plots, suggesting the accuracy of the slope calculated in the linear regression analysis. Additionally, as x tends toward zero the ratio should tend towards b/d. In order to confirm the accuracy of this measurement the offsets can be calculated directly from the zero intensity data.

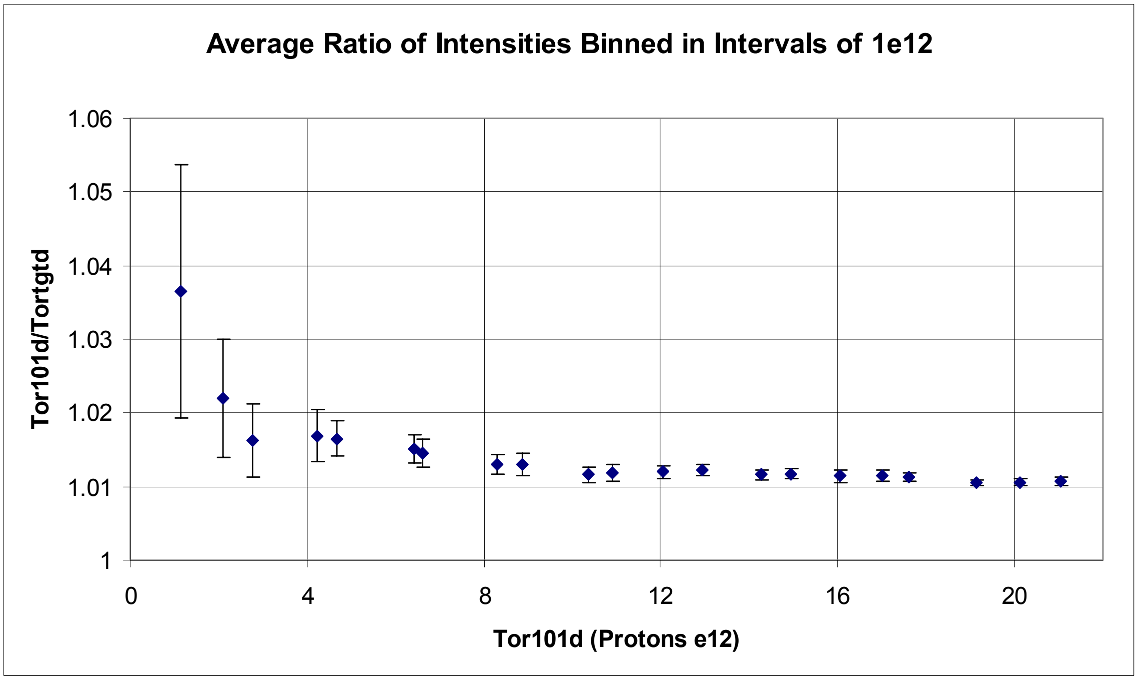

Figure 5: The ratio of Tor101d intensity to Tortgtd intensity averaged in bins of 1e12 protons plotted against Tor101d intensity

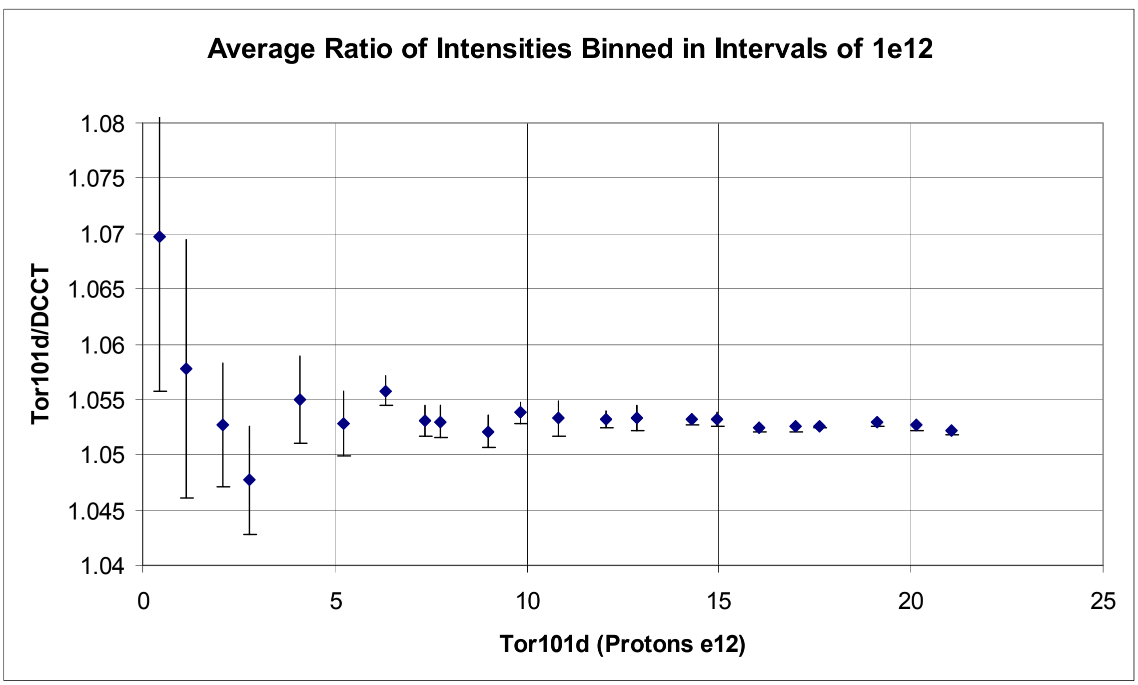

Figure 6: The ratio of Tor101d intensity to the DCCT intensity averaged in bins of 1e12 protons plotted against Tor101d intensity

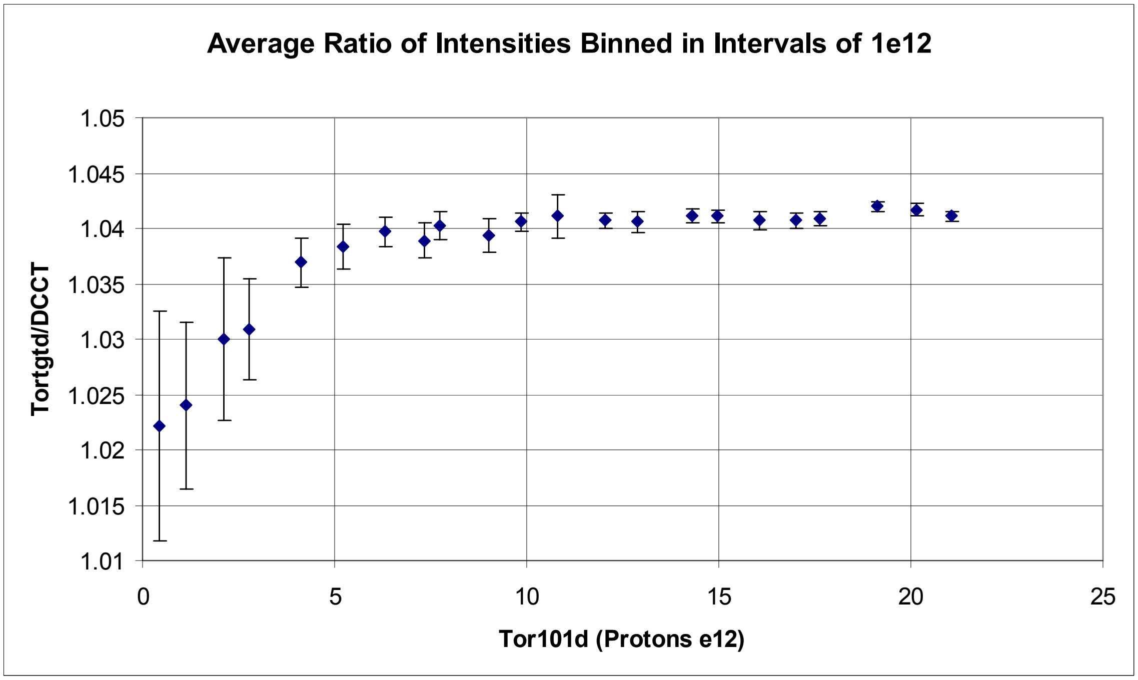

Figure 7: The ratio of Tortgtd intensity to the DCCT intensity averaged in bins of 1e12 protons plotted against Tortgtd intensity

Figure 8 shows the intensity readings of the three sensors when there is no beam. Each data point is the average intensity over a six hour time period; the error bars reflect the standard deviation of each six hour bin. Similar data was generated binning every 3, and 12 hours. The general pattern of the data was the same, and the average standard deviation for all three plots was almost identical. This suggests that the standard deviations reflect the spread of the data rather than fluctuations in the averages from one time period to another.

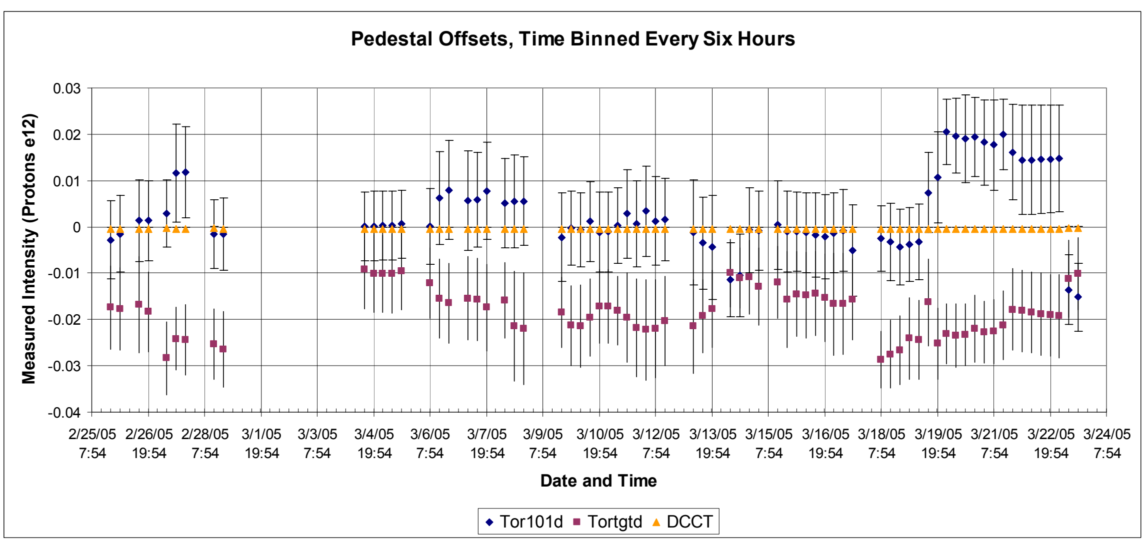

Figure 8: Zero intensity data averaged ever six hours

Averages from the data in Figure 8 were used to calculate the pedestal offsets, and are tabulated below. There is an unexplained jump in the Tor101d offset around March 20th. At this time the beam was run at intensities between 8.5e12 and 9.5e12 protons per pulse. Therefore, the data only reflects one intensity bin (centered at 9e12 protons). The offset during this time has negligible impact on the y-intercept of the linear fits. Furthermore, there is a high density of points in this region, (roughly 25%), due to high spill rate. Including all of these points in the pedestal calculation would unfairly bias the offset, so these points were not wholly included. The ratios of the linear coefficients, and the y-intercepts were also calculated and compared with the results of the linear regression analysis, as seen in Table 2. All of the results agree to a fairly high degree of precision.

Table 1: Pedestal Offsets from the Zero Beam Data Set

	Pedestal Offset (Protons e12)
Tor101d	0.0050
Tortgtd	-0.0207
DCCT	0.0000

Table 2: Comparisons of the ratios of linear coefficients and y-intercepts from the linear regression analysis to the ones taken from the ratio plot curve fits, and pedestal offsets.

	Slope from the Linear Regression	Fit of Ratio Plot as actual intensity goes to infinity	y-intercept from the Linear Regression (Protons e12)	y-intercept Calculated from the Pedestals (Protons e12)
Tor101d vs Tortgtd	1.0097	1.0106	0.0259	0.0259
Tor101d vs DCCT	1.0525	1.0526	0.0050	0.0055
Tortgtd vs DCCT	1.0424	1.0416	-0.0199	-0.0202

The values for the pedestals, and linear coefficient ratios were used as constraints for fits to the ratio plots (not shown). This left an absolute value for one of the linear coefficients as the only input. The fits replicate the data fairly well, and were not particularly sensitive to variations in the input parameter.

During the 23rd of March a problem occurred with the NuMI target causing the beamline to be turned off. However, the intensity was stilled measured by all three sensors for the next several hours. The final two data points in Figure 8 reflect this time period. The pedestal offsets for both of the toriods were greatly effected by the shutdown of the beam; both moving closer toward zero, and toward each other. This suggests that the toroids are affected by the components in the beamline, and that the calibration of the toroids was done with these components off. Pedestal offsets could therefore be reduced by recalibrating with the beamline components turned on. Furthermore, this data was not used to determining the pedestals for comparison with the other plots, as they do not accurately reflect the offset during run conditions.

<u>Calibration Timing</u>

In order to account for the observed discrepancies between the DCCT and the toroids the timing of the gate in reference to the beam was checked, and compared to that of the calibration pulse. The timing was off by about 3 MI revolutions which amount to roughly 30 usec. To be sure of the timing offset pictures from the online oscilloscopes attached to Tor101 and Tortgt were taken during a target scan on April, 25. The relative position of the beam within the gate was measured on the oscilloscope and the results (tabulated below) confirmed the prediction. Along with the data in Figure 1, which gives the error per usec from the calibration time in the gate, this information was used to calculate error associated with the timing offset.

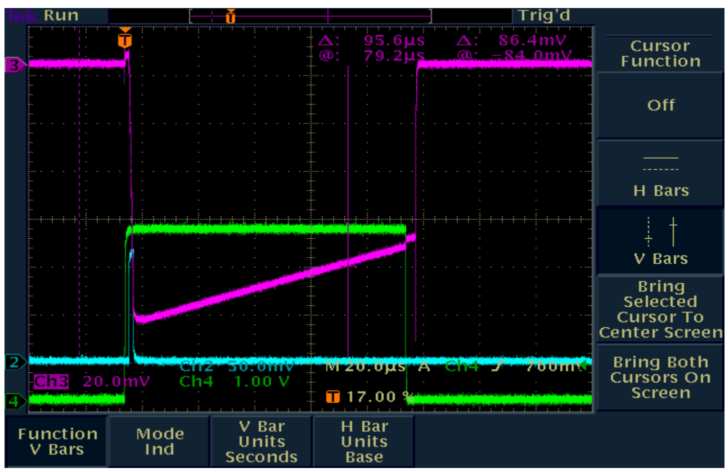

Figure 9: Position of the calibration pulse (cyan) in the gate (green). The slope of the integrator signal (magenta) after the integration of the pulse gives rise to the error associated with stepping the pulse through the gate. The slope is independent of pulse position, and therefore the error is a linear function of the distance between the pulse and the end of the gate. Since the calibration pulse is 1.6 usec inside of the gate, that position is associated with zero error.

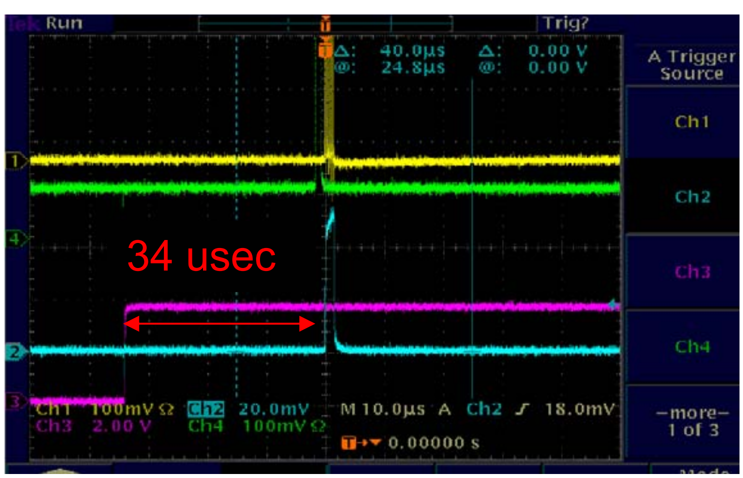

Figure 10: Position of the beam (cyan) in the gate (green) for Tor101.

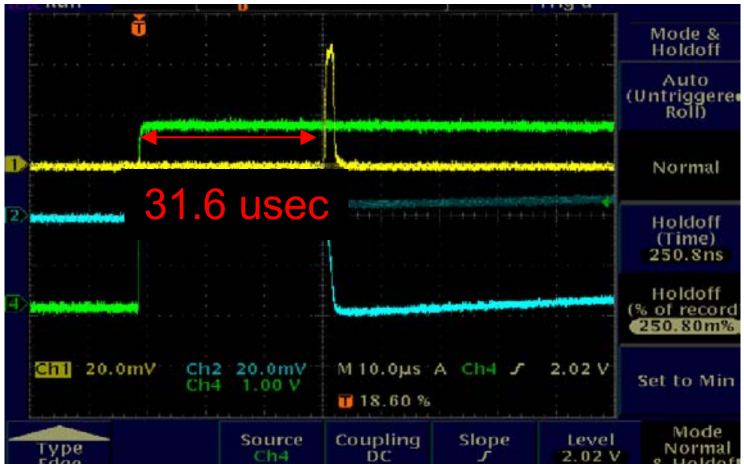

Figure 11: Position of the beam (cyan) in the gate (green) for Tortgt.

Table 3: The relative timing of the beam and calibration pulse in the gate, and the associated error.

	Position in the gate (usec)	Position Relative to Calibration Pulse (usec)	Resulting Error (%)
Calibration pulse	1.6	-	-
Tor101d	34.0	32.4	4.86%
Tortgtd	31.6	30.0	4.50%

The errors calculated in Table 3 are based on 0.15% per usec, and zero error at the calibration time of 1.6 usec inside the gate. These assumptions may not hold and most likely differ slightly between the two toroids. These calculations, however, give a fairly good estimate, and show that a large portion of the observed discrepancy between the toroids and the DCCT can be corrected by aligning the timing of the beam and calibration pulse in the gate.

Conclusions

The stability of the pedestal offsets are not yet fully understood, although there does seem to be a correlation between the offsets and the beamline status. Other environmental factors like temperature may also contribute, as well as unforeseen behavior in the electronics. The pedestal on the DCCT is nearly zero and does not pose any problems.

The two toroids differ in pedestal offsets by, 2.5e10 protons, and scale with a 1% difference. Although, this is within acceptable errors it would be better to understand the source of this difference, and reduce it. The 4.24% to 5.25% difference seen between the toriods and the DCCT is of much greater concern. The largest source of the error comes from the discrepancy between the calibration pulse and the beam, specifically their relative positions in the gate. Once this problem is fixed the errors should decrease to within a more acceptable range. There are, however, other avenues to pursue that might result in even greater accuracy in the toroids. A stable voltage source that would allow full scale calibration has been recently acquired. Also, five pulse signals that accurately recreate the five batch beam can be used in future calibrations. When the target is fixed and normal operations commence, these changes can be implemented, and the overall agreement between the three sensors can be reevaluated.

Another option to consider for the future is to incorporate a device that calibrates the toroids prior to each pulse. Working on a similar principal to the current calibration, known currents are passed through the toroids and the response is measured. However, this device would be triggered by NuMI events to recalibrate for each spill. This would resolve any drift issues, and correct for environmental influences such as temperature, and beamline induced ambient fields.